Meta-analysis of country-specific energy scenario studies for neighbouring countries of Germany

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ABSTRACT

The environmental impact of the energy sector and its substantial economic scale lead to the conception of a large number of studies by a wide variety of stakeholders in the field. These studies investigate the possible evolution pathways of the energy systems in form of multiple scenarios, and may cover both a national and an international scale. The high connectivity of the European electricity grid results in a dependency of the national energy systems with each other. Hence, knowledge about the possible energy futures of neighbouring countries is crucial to make well-informed decisions for a national energy policy. This work thus consists of a meta-analysis of country-specific energy scenario studies for 15 neighbouring countries of Germany. This analysis is then compiled into 1) the country profiles, which consist of country-specific cause–and–effect relationships concerning various energy-technical aspects and 2) the analysis charts, from which a generalized overview spanning the energy futures across all countries has been achieved.

Keywords: Energy scenarios, European countries, Energy demand, Renewable energy targets

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1. INTRODUCTION

In light of the climate resolutions adopted in the Paris Agreement of November 2016 and the recent Climate Change Conference of the United Nations in December 2018, the public and the policy makers are continuously transforming the discussion on the means of energy supply and consumption in many countries. Potential decarbonization pathways from global to regional scale are analyzed and assessed in form of scenario studies. These studies often consider a multitude of scenarios, each of them described by a variety of assumptions. Those scenarios are then mostly compared against a reference scenario that represents the status quo. The studies thus offer comprehensive insights on the status quo of a country or region and also explore possible pathways that diverge from it; along with the prevalent technologies, emission targets and potentials.

1.1 Europe-wide scenario studies

Scenario studies that cover the entirety of the European countries include the Ten Year Network Development Plan of ENTSO-e (ENTSO-e (2018)), World Energy Outlook (OECD/IEA (2018)) of the International Energy Agency or the e-Highway2050 (EC-FP7 (2015)) and the EU Reference Scenarios (EC (2016)) sponsored by the European Commission. Despite their similar aim and overall scope,

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comparing such scenarios comprehensively poses several challenges. First, the regional, temporal as well as energy system scope of most studies are non-coherent. For example, while the EU reference scenario only focuses on the EU28 countries, the e-Highway 2050 describes scenarios considering their model results of the sub-national representation of the countries described by the term EU28+[1], the ENTSO-e models the development in the EU28+ countries but additionally considers Turkey, and the World Energy Outlook, as the name suggests, takes a global perspective on the European energy system development. Additionally, the scenarios vary in the presented model time horizon (while most scenarios are developed for the time frame from 2020 to 2050, the World Energy Outlook and the ENTSO-e scenarios end by 2040 while the EU reference scenario diverges by uses 2010 as a base year) and energy system scope. Second, the assumptions on technical development and public acceptance varies widely among the scenarios. Thus, there exists no consensus on, if ever, and if, then starting from which date, technologies such as carbon-capture and storage (CCS) or green fuel refining will be commercially utilized. Third, the scenarios differ in their assumptions about future policy adoption. In other words, there exists no common unanimity about the future of regulation based developments such as the nuclear power phase-out (Figure 1), the ban of all or certain types of combustion engine vehicles, or the preferred subsidy scheme for "green-mobility". Last, not all of the presented scenarios meet the ambitious emission mitigation goals set by the European Union for 2020 and 2050 leading to a broad range between the various scenario boundaries.

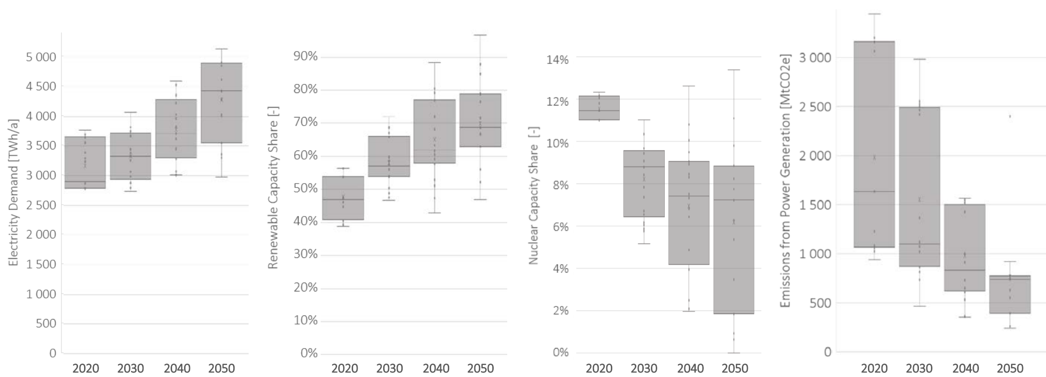


Figure 1: Results of the comparative meta-analysis of the pan-European scenarios.

Regardless of the many differences in the scenario setup, most scenario results show similar trends concerning the major scenario indicators such as greenhouse gas emissions, electricity demand and renewable power use (Figure 1). Namely, all scenarios foresee a rise in electricity demand which will be supplied by mostly renewable energy. While the share of installed renewable electricity generation by 2050 varies between 47% to 97%, the achieved emission reduction in the power sector varies significantly less (between 60%-87% in 2050 compared to 1990 values).

1.2 Aim of this study

By 2050, the climate protection targets of Germany are set at a reduction in greenhouse gas emissions by at least 80% (and up to 95%) and achieving a share of renewable energies in gross end energy consumption of 60% compared to 1990 (BMU (2016)). Among others, reaching these goals would entail the large-scale expansion of current renewable energy technologies and possibly the emergence of new ones, decarbonizing the heating and mobility sectors through electrification of these, partial or complete phase-out of fossil-fired power plants, and grid expansion in order to benefit from the increased flexibility and smoothing effects. However, since Germany is part of a synchronous European

[1] The term EU28+ refers to the meta-region consisting of the EU28 countries together with Switzerland and Norway.

grid, its energy system is also connected—physically and socio-politically—with the energy-political evolution of its neighbouring countries. Thus, having an overview regarding the current energy-technical discussions taking place in these countries would lead to more informed energy-political decisions for the future. This study therefore consists of a meta-analysis from a collection of energy scenario studies, which had been conducted specifically for individual neighbouring countries of Germany.

2. SCOPE OF THE META-ANALYSIS

In this section, the scope of this review study is described. The work lays the focus on the fifteen electrically connected neighbour countries of Germany: Belgium, Denmark, United Kingdom, France, Italy, Netherlands, Norway, Austria, Poland, Sweden, Switzerland, Slovenia, Czech Republic, Slovakia and Hungary. In order to determine the specific discussions on the national energy policies, this review excludes the whole European scenario studies.

By focusing on the country-specific studies, we believe that the energy-technical discussion points within a country can be more closely identified, and the reconciliatory biases arising from a continental point of view–e.g. matching between import/export dependencies across countries–can be minimized. Moreover, in this work, only the studies which were conducted after 2009 are taken into account to ensure that the individual policies and targets that are considered in the studies are sufficiently up-to-date (not older than 10 years).

2.1 Key figures

Within the scope of this work, 34 country-specific studies have been reviewed, which depict 126 scenarios in total. Figure 2 gives an overview on the key figures of the study, and Table 1 provides a listing of the references for each study along with their respective countries.

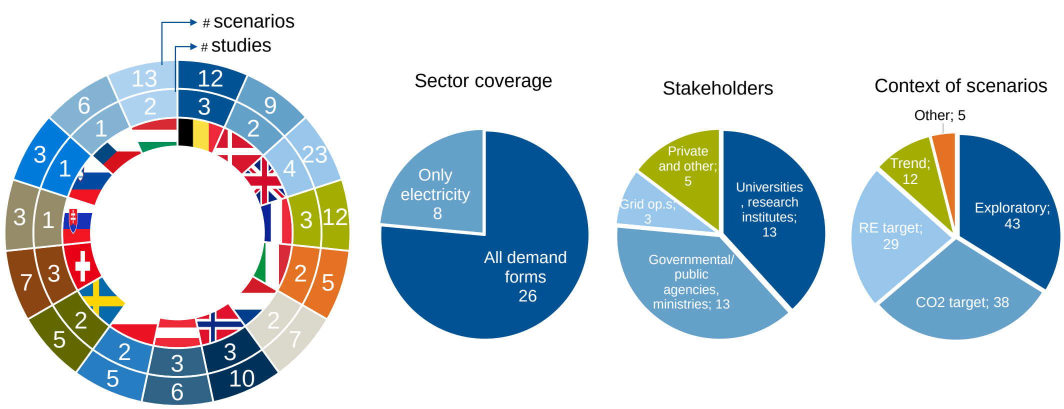


Figure 2: Key figures of the meta-analysis.

One challenge when bringing such a large set of independent studies into a common context to enable comparability stems from their inhomogeneity. To quantify the various aims and scopes of these studies, an assessment is made as follows:

1. *Sector coverage:* It has been recognized that not every scenario study covers all of the end energy forms of electricity, heating/cooling and mobility. From the 34 considered studies, 26 span all demand categories, whereas the rest eight focus on the electricity sector only.

2. *Types of scenarios:* The outcome of an energy scenario is based on its type. Out of the 126 scenarios:

Table 1: Scenario studies considered in the work.

Country	References
Belgium	Elia (2017); FPB (2017); Energyville (2017)
Denmark	Aalborg Universitet (2015); Energistyrelsen (2014)
United Kingdom	National Grid (2018); KPMG (2014); ICL (2016); UKERC (2013)
France	ADEME (2014); négaWatt (2017); RTE (2017)
Italy	MSE (2017); AIEE (2017)
Netherlands	CE Delft (2017); ECN (2017)
Norway	CenSES (2014); NITO (2009); UiO (2014)
Austria	Umweltbundesamt (2015, 2016); TU Wien (2017)
Poland	Forum Energii (2017); PAIH (2013)
Sweden	IVL (2011); SEA (2016)
Switzerland	Prognos (2012); BfE (2017); PSI (2014)
Slovakia	MHSR (2014)
Slovenia	MZI (2018)
Czech Republic	MPO (2014)
Hungary	Wuppertal Institute (2016); MoND (2012)

- 38 were identified as CO_2-target scenarios, which set fixed targets for the annual CO_2 emissions for the end year of simulation, or defining a carbon budget up to that year,
- 29 as target scenarios on renewable energy shares, which define lower bounds for the share of renewable energy or electricity by a given year,
- twelve as trend (business-as-usual) scenarios, which depict a projection of the status quo with the respective policies carrying on as planned,
- 43 as exploratory scenarios, which investigate various plausible futures diverging from the trend without explicit emission or renewable energy targets.

It has to be pointed out that while a direct comparison between two scenarios of different types (e.g. a trend and a net zero carbon scenario) is not meaningful, this totality of scenarios establish a wide range within which future developments can take place in a given country.

3. *Stakeholders:* The context of a scenario study depends on the stakeholders involved in its production, such as the organizations which conducted it or those which it was conducted for. For instance, the studies conducted by research institutes or public agencies may focus on the rather extreme deep decarbonization and 100% renewable electricity scenarios. On the other hand, the focus may lie on trend scenarios for studies that were carried out by/for private organizations, which would then allow economic feasibility assessments for the most likely future developments. Regarding our collection, thirteen out of the 34 studies were conducted by universities and research institutes, another thirteen by governmental/public agencies or ministries, three by grid operators and five by other private organizations and unions.

3. METHODS AND RESULTS

This section describes the methods with which generalized, energy-related statements were derived in this meta-study, and describes the country profiles with an example. For the total extent of the work, the reader is encouraged to follow the link provided in Section 5 ("Complementary Material").

3.1 Country profiles

In order to gain insight regarding the national course of energy-related discussion in each country and also to establish points of comparison between multiple studies within the country, five energy-technical *indicators* are identified as common aspects recurring in almost every energy scenario study:

1. changes in the energy demand,
2. shares of renewable electricity,
3. nuclear targets,
4. decarbonization targets,
5. import/export dependencies.

Then, by considering each of these indicators, causal relationships are identified for each individual country and compiled as *country profiles* (Figure 3).

ELIA [5]	Indicator	■ Targets / ■ Causes	■ Requirements / ■ Outcomes
	Energy demand	■ Electrification in heating & transport + energy efficiency	■ FEC ↓, electricity consumption ↑
	Share of renewable energies	■ High share of RE	■ Strong grid, flexible fleet & demand, and storage required
	Decarbonization	■ 80% reduction in GHG emissions (1990-2050)	■ Around 90% carbon-free electricity required
	Nuclear targets	■ Nuclear phase-out by 2025	■ New thermal capacity (+3.6 GW) required
	Import / export	■ Competitive prices compared to neighbours	■ New interconnectors (+4 GW) and efficient CCGT required

Federal Planning Bureau [6]	Indicator	■ Targets / ■ Causes	■ Requirements / ■ Outcomes
	Energy demand	■ High CO_2-elc. price and efficiency (-), growth (+)	■ Near constant (+0.1%/a) FEC, growing (+0.8%/a) electricity
	Share of renewable energies	■ 13% of gross final energy consumption by 2020	■ 12% in 2030, 16% in 2050
	Decarbonization	■ Higher RE, CHP & import, shutdown coal plants	■ 10% reduction in total CO_2 (2015–2050)
	Nuclear targets	■ Nuclear phase-out by 2025	■ Surge in gas-fired power generation by 2020
	Import / export	■ Unavailability of the nuclear fleet + high VRE	■ Rise in net imports between 2030–2050; up to 25 TWh/a

Figure 3: Country profiles – Example Belgium (1).

To be presented in these country profiles, up to two studies are selected for each country. Then, the storylines that were depicted in one or multiple scenarios within each study are used to derive either a "target → requirement (T2R)" or a "cause → outcome (C2O)" relationship for every indicator. An example of the former—in the scenarios depicted in the Elia (2017) study, nuclear phase-out is targeted by 2025, which in turn necessitates a further expansion of the thermal power plants by at least 3.6 GW (and more depending on the specific scenario). An example for a C2O relationship, on the other hand, can be seen on the FPB (2017) study; as Belgium phases out its nuclear fleet and achieves high variable renewable energy capacities by 2050 in the business-as-usual scenario portrayed in this study, the net imports will have to rise, up to 25 TWh per year.

By observing the commonalities between the study-specific statements depicted on the country profiles, general narratives for a given country can then be derived. For example, across each scenario, 1) nuclear phase-out is carried out by 2025 in Belgium, 2) additional thermal capacity and/or interconnectors become necessary for covering the baseload and 3) wind power becomes a major renewable electricity contributor.

Besides the qualitative statements concerning the energy-technical indicators, the country profiles also include a quantitative comparison of the yearly changes in the electricity demand and the share of renewable electricity in the total production, across each scenario including the EU Reference scenario (EC (2016)) of the respective country (Figure 4). Variance in the numbers is illustrated under various boundary conditions that each scenario postulate—a smaller spread implying a higher agreement between scenarios.

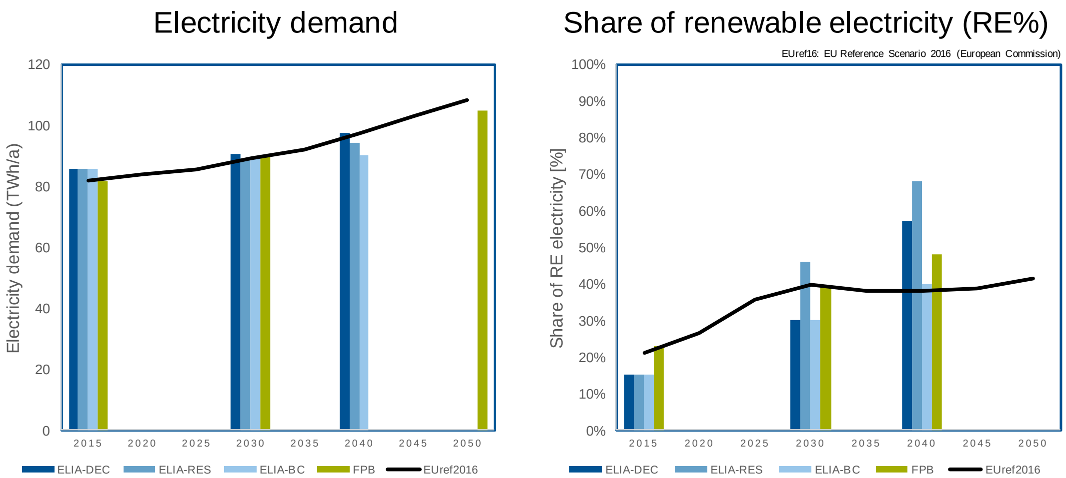


Figure 4: Country profiles – Example Belgium (2).

3.2 Analysis charts

Additional to the country profiles, generalized *analysis charts* are plotted to get an overview across all countries, using quantifiable metrics related to each of the indicators, except the fourth indicator. For example, for the indicator "changes in the energy demand", the general trend towards electrification of sectors is investigated by comparing the changes in the annual electricity demand and the total energy demand between the first and latest simulated years of the study. These charts thereby enable a unified comparison across every study and thereby constitute the main added value of this meta-analysis. The key results obtained from the analysis charts will be explained in the following subsections.

3.2.1 Changes in the energy demand

As mentioned above, in Figure 5 each scenario that includes the corresponding quantitative data is mapped on a coordinate system, whose horizontal and vertical axes represent the percentage changes in the 1) final energy and 2) electricity demand between 2015 and 2050[2], predicted by the scenario. These scenarios are also labeled by the respective country that they apply to, and are color-coded for their type.

From the figure, it is observed that the majority of the scenarios fall into the second quadrant, which corresponds to a decrease in the final energy consumption and an increase in the electricity demand. Depending on the country, a combination of increasing energy efficiency measures and the electrification of the end use sectors account for this result. In particular, electrification in transport sector was mentioned by the studies for 14 of the 15 countries, and in residential heating for 12 of the 15 countries. On the other hand, another set of scenarios fall into the first quadrant where both demand categories increase. This outcome stems from further economic growth and is observed more often in the scenarios conducted for the central European countries. The scenario types have a visible influence on the outcomes—most of the trend and exploratory scenarios predict very minor changes

[2]For studies not simulating until 2050, the latest simulation year is taken instead.

in the final energy and limited changes in the total electricity consumption. On the other hand, CO_2 target scenarios necessitate significant reductions in the final energy consumption.

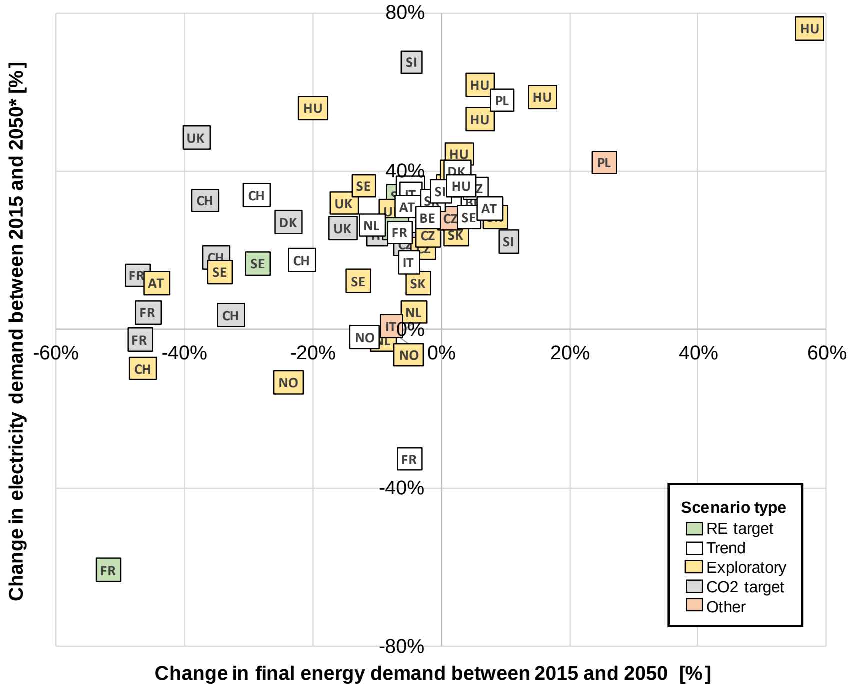


Figure 5: Changes in the final energy and electricity demand between 2015 and 2050 for each investigated scenario. For studies not simulating until 2050, the latest simulation year is taken instead.

3.2.2 Shares of renewable electricity (RE)

In Figures 6 and 7, each scenario is located on the vertical axis depending on the achieved share of the renewable electricity in the total power demand by their end year of simulation. The vertical axis signifies the prevalent RE technology—by the absolute amount in Figure 6 and by the relative increase between 2015 and 2050 in Figure 7. In terms of the absolute values, hydropower and wind energy are observed to be the technologies which will produce the majority of the renewable electricity for most of the countries. Here, the dominance of hydropower comes from the high-potential sites which are already utilized to a large extent in countries such as Austria, Norway and Switzerland. On the other hand, higher capacity factors achieved by wind energy in Europe compared to solar makes it the more relevant choice for volatile RE production. Across all scenarios, a wide range of RE shares between 10% and 100% of total electricity are projected, whereas the 100% RE outcomes consist mainly of exploratory or RE target scenarios.

If emerging RE technologies, i.e. the technologies for which the highest expansion takes place are considered (Figure 7), wind and solar energy are leading for large number of countries (53% of all scenarios for wind, 20% for solar). As mentioned above, the fact that most of the hydro sites are already utilized, combined with the regulatory difficulties limit the expansion of hydropower compared to other RE technologies—as only Norway has multiple scenarios where the hydroelectricity enjoys the largest increase.

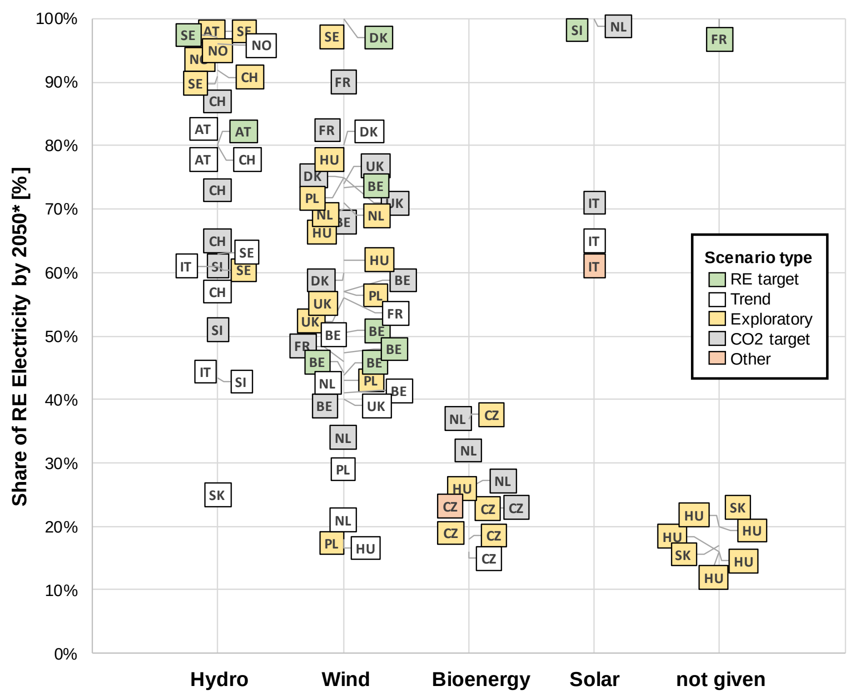


Figure 6: Share of electricity production from RE by 2050 for each investigated scenario, horizontal axis representing the dominating RE technology for the respective scenario. For studies not simulating until 2050, the latest simulation year is taken instead.

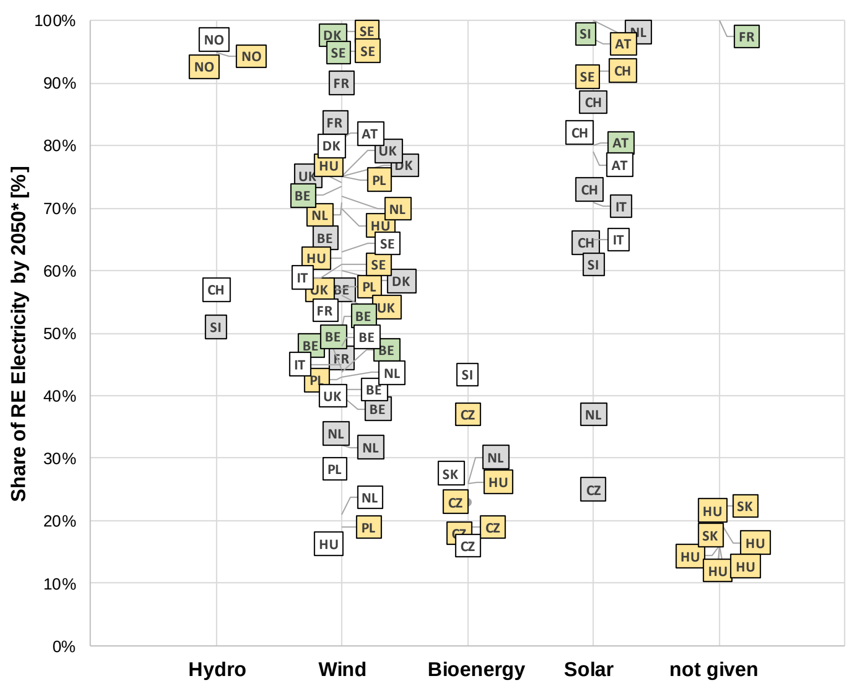


Figure 7: Share of electricity production from renewable energy by 2050 for each investigated scenario, horizontal axis representing the RE technology where the highest increase occurs between 2015 and 2050. For studies not simulating until 2050, the latest simulation year is taken instead.

3.2.3 Nuclear targets

Figure 8 consists of bar charts for every county, showing the fractions of the nuclear *outcomes* that each scenario within a country achieves in the end year of simulation. Here, four such outcomes are defined:

1. the country does not have any nuclear power plant and does not plan to build one ("no nuclear"),
2. the country possesses nuclear power which is actively phased-out ("phase-out"),
3. the country owns nuclear power plants that are still operational, but no new unit is built ("no phase-out"),
4. the country plans new nuclear power plant installations ("expansion").

As seen in the figure, when it comes to the prospects on nuclear power, a wide variety of the mentioned outcomes are present among the analyzed studies. In particular, four of the 15 countries (Austria, Denmark, Italy and Norway) already have no nuclear power, whereas Belgium and Switzerland target phase-out in each of the scenarios associated with them. On the other hand, countries such as UK, Czech Republic and Slovakia target nuclear expansion in the majority of their scenarios. For Hungary, Netherlands and Sweden, multiple outcomes of further expansion, no phase-out and phase-out are present; implying the lack of a finalized plan on nuclear to date.

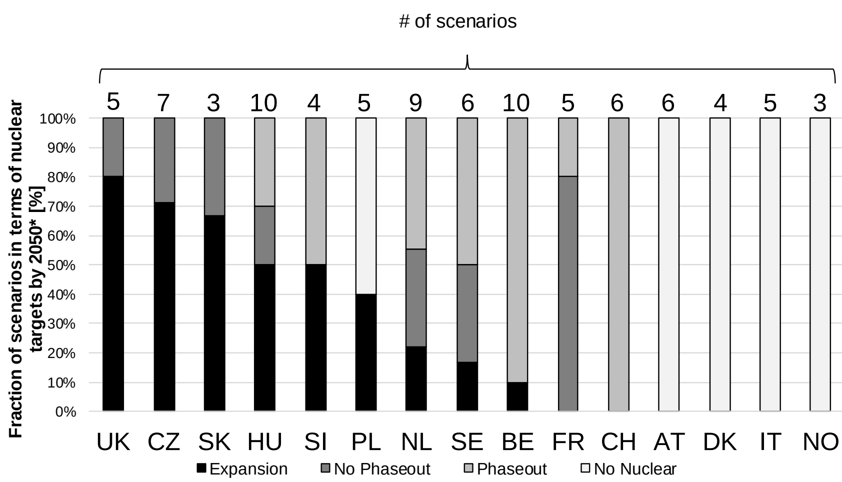


Figure 8: Set (or achieved) nuclear targets by 2050 for each investigated scenario. For studies not simulating until 2050, the latest simulation year is taken instead.

3.2.4 Import/export dependencies

Since continental Europe is connected by a synchronous network which allows cross-country power exchange through electricity markets, the energy system of each country is physically coupled with each other via their import and export activities. In this regard, Figure 9a shows for each country the fraction of the scenarios, in which either:

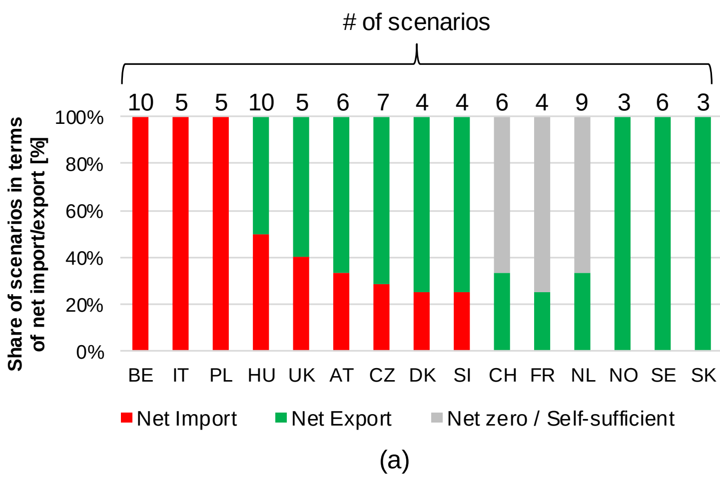
1. the yearly imports exceed the yearly exports by the end year of simulation ("net import"),
2. the yearly exports exceed the yearly imports by the end year of simulation ("net export"),
3. the yearly exports are forced to be equal to the yearly imports, or no power exchange with other countries is allowed at all ("net zero/self-sufficient").

As far as these national import and export outcomes are concerned, Belgium, Italy and Poland stand out as the countries where each scenario predicts positive net import of electricity by the end of their simulation period. On the other hand, each scenario for Norway, Sweden and Slovakia predicts the generation of surplus electricity (former two via hydropower, latter via new nuclear) which, in turn, creates export potential into neighbouring countries. In general, the number of net export studies are higher than the number of net import studies. This is also visualized on by Figure 9b, where each country is color-coded from red to green depending on a metric of self-sufficiency. This metric is defined as follows:

$$\text{Self-sufficiency} = \frac{N^{\text{scenarios}}_{\text{net export}} - N^{\text{scenarios}}_{\text{net import}}}{N^{\text{scenarios}}_{\text{total}}}, \tag{1}$$

so that it has a value between -1 and 1, both extremes entailing that the country has only net export or net import scenarios respectively.

As observed in the figure, most countries, including those which directly neighbour each other, predict a net-export future. While it might still be possible for these countries to export their overproduction to those few import-anticipating countries (such as Italy, Belgium and Poland), this apparent asymmetry calls for further cooperation between countries in order to organize their import and export capabilities for the future.



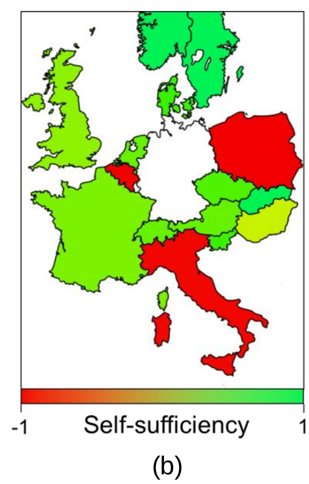


Figure 9: Classification of the scenarios for each country's import/export balance by 2050. For studies not simulating until 2050, the latest simulation year is taken instead.

4. DISCUSSION AND CONCLUSION

In this study, a meta-analysis of energy scenario studies has been conducted using country profiles and analysis charts, which enabled both country-specific and -overarching overview and comparison, despite the high heterogeneity of these studies. Through these representations, the possibilities within the wide spectrum of outcomes for each country are able to be identified. Particular insights were obtained from the analysis charts. All in all, the trend scenarios show no big changes in final demand, whereas there is a common progress towards electrification in transport and residential heating. Wind energy is identified as the most relevant expanding RE technology in the European market, whereas it competes with hydropower in terms of the annual electricity production. Import/export considerations discussed in each country-specific study were found to be lopsided in the favour of export, implying insufficient coordination between national policies. For only a few of the countries, nuclear phase-out is not discussed. On the other hand, more than half of the countries have at least one nuclear scenario, hinting that there is there is no common, conclusive ground regarding nuclear targets up to date.

5. COMPLEMENTARY MATERIAL

As complementary material, a repository including these country profiles can be found under the following link: https://github.com/sonercandas/energy_scenario_studies.

ACKNOWLEDGEMENTS

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